Energy Conversion and Management 91 (2015) 451–458

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Characterization and pilot scale fluidized bed gasification of herbaceous biomass: A case study on alfalfa pellets

Shiplu Sarker [a,*], Fernando Bimbela [b], José Luis Sánchez [b], Henrik Kofoed Nielsen [a]

[a] University of Agder, Faculty of Engineering and Science, Serviceboks 509, 4898 Grimstad, Norway
[b] Universidad Zaragoza, Thermochemical Processes Group (GPT), Aragon Institute of Engineering Research (I3A), I+D+i building, C/Mariano Esquillor s/n, E-50018 Zaragoza, Spain

ARTICLE INFO

Article history:
Received 26 August 2014
Accepted 13 December 2014
Available online 31 December 2014

Keywords:
Alfalfa pellets
Pilot scale fluidized bed
Gasification
Equivalence ratio
Temperature

ABSTRACT

Pilot-scale bubbling fluidized bed gasification tests of alfalfa pellets were performed at two different operational periods ranged on the basis of the two given equivalence ratio (ER) (the ratio between actual air and the stoichiometric air) namely as 0.25 and 0.30. During the test, the solid feeding rate was kept constant at 4.7 kg/h while the air input was varied and thus the ER. Increasing air from 4.16 to 4.99 N m^3/h contributed to the evolution pattern of several parameters such as the rise in gas lower heating value (LHV) and gas yield, the average maximum of which were 4.2 MJ/N m^3 and 1.5 N m^3/kg respectively. Gas composition was mainly boosted by the concentration of CO, as the rest of the combustible components stayed rather unaffected due to the modified air flow rate. The steady state bed temperature agreed with the trend of air flow and ranged between 720 and 780 °C despite gasification start-up occurred at 800 °C. Total char (~282 g/kg) and tar yield (~1.1 g/N m^3) showed reasonable values while tar composition was predominantly led by the amount of phenols.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

In the spectrum of renewable energy, biomass poses as one of the most important alternatives to fossil fuels [1], accounting as the fourth largest energy source [2] in the world after coal, petroleum and natural gas, and offering substantial advantages including no net [3] and even negative CO_2 emissions [4,5], depending on the use of CO_2 capture technologies. In fact, it is the only renewable source that can feasibly be transformed into various forms of fuels, i.e.: solids, liquids and gases, through different conversion pathways: thermo-chemical, bio-chemical and biological [2,6]. Within the thermochemical conversion routes [7] gasification is attractive owing to its flexibility and simplicity. The gas produced from biomass gasification is a clean (once it is adequately conditioned) combustible fuel typically consisting of CO, H_2, CO_2, CH_4 and C_2H_n, [8,9] which is viably used for a number of applications including heat, electricity or as a synthesis gas (or syngas) that can serve as raw-material in the manufacture of other value added products [10]. To achieve gasification, a series of reactors may be implemented, such as fixed-bed, moving bed, fluidized-bed and entrained flow gasifier [6]. For a suitable energy output and operational ranges each of these gasifiers has its own advantages and disadvantages. Fluidized bed (FB) gasifiers for instance are relatively less complex, flexible and efficient [11,12] and thus are used in numbers in medium and small scale applications [13].

In addition to the types of the gasifiers, various gasifying agents such as air, steam, steam–oxygen and CO_2 can significantly influence the output quality and performance of gasification [11,14]. The choice of gasification hence is not only a choice of a gasifier but also a choice of the gasifying medium. Air as a gasifying agent despite yielding a low heating value gas, has certain advantages over others [11]. Air is easily available everywhere and its introduction to gasification does not incur additional costs for its production, thus as a medium invariably emerges as cheap, easy and readily available option for various scales of operations, as does in this study.

Although a great deal of biomass feedstocks have already been explored in fluidized bed gasification, the work in regards to herbaceous biomass especially to alfalfa (*Medicago sativa* L.) is potentially scarce. The majority of efforts for this biomass to date have only been paid to pyrolysis [15,16] and characterization [17] with a noted investigation primarily toward fixed-bed downdraft gasification [18]. But considering the potential of environmental and financial advantages [19] including with lignocellulosic properties, alfalfa could be an attractive fuel for distributed power generation where the possibility of fluidized bed gasification is enormous [20]. The focus of the present study thus is to utilize alfalfa pellets (that does not compete with the animal feeding) for a pilot-scale fluidized bed gasification, which can serve as a means of producing

---

* Corresponding author. Tel.: +47 37233144.
E-mail address: shiplu.sarker@uia.no (S. Sarker).

http://dx.doi.org/10.1016/j.enconman.2014.12.034
0196-8904/© 2014 Elsevier Ltd. All rights reserved.

renewable energy to the areas de-centralized from the national electricity grid.

As a local biomass, alfalfa has vast potential around the Ebro valley area in the Northeast (NE) Spain, constituting the regions of Aragon and Catalunya, with available lands of 107,000 and 42,500 ha respectively. Of the total available land for the alfalfa in Spain, 58% is covered by these regions, with average dry matter (DM) yields of about 17 t ha^{-1} y^{-1} [19]. The majority of this yield is primarily realized through pelletization [21] which in terms of energy production is also interesting as pellets are easy-to-handle, superior than to other forms of biomass. Alfalfa pellets are thus utilized in the present context of gasification.

Research in regards to pilot-scale fluidized bed gasifier is extensive [13,22–26] and has been conducted for a number of feedstocks operating with a number of experimental conditions. In a recent work by Campoy et al. [13] for example a pilot-scale BFB (Bubbling fluidized bed) gasifier was involved to process five different biomass: wood pellets, orujillo, meat and bone meal (MBM), dried sewage sludge (DSS) and municipal solid waste (MSW) for a number of operating conditions, i.e.; bed temperatures (770–870 °C) and ERs (0.23–0.43) for which gasification performance was compared among the feedstocks. A comprehensive other research [22] furthermore included ten biomass (ranging from woody to agricultural) to test simultaneous gasification and energy conversion by a pilot scale air-blown fixed-bed downdraft gasification power plant unit for which operational parameters was observed as against different syngas flow rates (105–211 N m^3/h). Documented researches [27,28] also considered co-gasification of a wide range of biomass for the pilot-scale studies, utilizing different modes of gasification system.

In line with these efforts, the preliminary work presented here introduces alfalfa pellets to a pilot-scale bubbling FB reactor with a purpose of evaluating gasification for a range of bed temperatures (720–780 °C) and ERs (0.25–0.30).

2. Materials and methods

2.1. Feedstock

Herbaceous biomass alfalfa pellets (average dimensions: approximately 6 mm Ø and 25 mm length) were used as feedstock for this study. Approximately 100 kg of alfalfa pellets with 100% purity from the first harvest (April 2013) were manufactured by Cooperativa Campo San Gregorio and kindly supplied by Molinos Afau S.L., both established on Pina de Ebro (Spain).

Alfalfa was grown and harvested around the Ebro valley, in the surroundings of Pina de Ebro, a village located 40 km southeast from Zaragoza (capital of Aragón, a region in the Northeast of Spain, coordinates: 41°39′0″N, 0°53′0″W). Generally, alfalfa grown in this region is harvested two/three times per season in the rainfed areas or six/seven times per season under irrigation [29] areas. To produce pellets, harvested alfalfa was first dried to approximately 10% of moisture by employing a rotary drum dryer, using flue gas as the drying medium. Dried biomass was then sent to a hammer mill equipped with a screen size of 3.2–6.4 mm, grinding the biomass to particles suitable for pelletization. As soon as the alfalfa was ground, it was delivered to the press mill consisting of a roller and heated die drilled with a series of perforated holes (~6 mm) through which biomass was squeezed. No external binders or stabilizing agents were used in the pelletizing process. The raw pellets exiting from the die were hot which was cooled to an ambient temperature of about 5 °C in the cooler and conveyed for further storage. A blade was typically used to cut the pellets to a predefined length, as those proceeded to the exit.

2.2. Characterization of feedstock

Alfalfa pellets were characterized in terms of moisture, ash, volatiles, fixed carbon, calorific values and of elemental compositions to examine the possibilities for gasification.

Moisture content of the alfalfa pellets was analyzed per triplicate as according to the standard ASTM D-871-82. Volatile matter was measured per triplicate based on the protocol suggested by EN 15148 while the protocol EN 15403:2011 was used for determining the ash content. Before the analyses of volatile matter and ash, biomass pellets were milled to an average particle size of <5 mm by using a lab-scale hammer mill (Mercanofil.Mateu y Solè, Spain). The calorific value of the alfalfa pellets was determined per triplicate using a calorimetric bomb (IKA C2000, Germany) complying with the standard ASTM D 4809-95.

Finally, the ultimate analysis was performed by using an elemental analyzer (Leco TruSpec Micro, USA) by which a simultaneous determination of C, H, N and S was obtained. As oxygen content cannot be analyzed directly by the present instrument, it was calculated by-difference.

In addition to the ultimate and proximate analyses, structural analysis in terms of cellulose, hemicellulose and lignin content of different sections of alfalfa crop are presented in Table 1 as according to the Refs. [30,16].

2.3. Pilot scale fluidized bed gasification

Gasification experiments were carried out by a pilot-scale bubbling fluidized bed gasifier located at Universidad Zaragoza, rated with an approximate maximum throughput capacity of 10 kg/h and operating at autothermal regime once that the temperature inside the reactor rises high enough to maintain gasification conditions. A global view of the gasifier, along with the associated components is illustrated by Fig. 1 while the following sub-sections discuss their working principles, as found during the operation of the plant.

2.3.1. Feeding system

The feeding system is composed of two hoppers of approximately 40 kg of capacity each, with their corresponding screw feeders that can be regulated independently with variable frequency drivers, discharging the solids into a third screw feeder (from now on, named as shuttle). One of the hoppers contains the raw material and the other is filled with silica sand, which is used as coadjutant material to aid feeding the raw material into the reactor, as well as to constitute the reaction bed.

Biomass and sand as contained in the hoppers were continuously introduced at the bottom of the reactor by means of the shuttle. The motion of the shuttle is expressed by the revolution per minute (rpm) and controlled by a variable frequency driver, adjusted to the necessary set-point in order to achieve the desired solids feeding rate. Prior to the tests, a calibration of the screw feeders from the hoppers was done.

2.3.2. Fluidizing agent and preheating

Air that used for gasification was preheated during the start-up by a ~15 kW electric heater (Tellsa, Spain). The fluidizing agent is

Table 1
Structural composition of alfalfa.

	Cellulose	Hemicellulose	Lignin	References
Alfalfa hay, matured, % (DM)	29.6	14	14	[30]
Alfalfa hay, weathered, % (DM)	30	13	15	[30]
Alfalfa, early bud (g/kg DM)	265	122	141[a]	[16]
Alfalfa, full flower (g/kg DM)	285	123	169[a]	[16]

[a] Klason lignin.

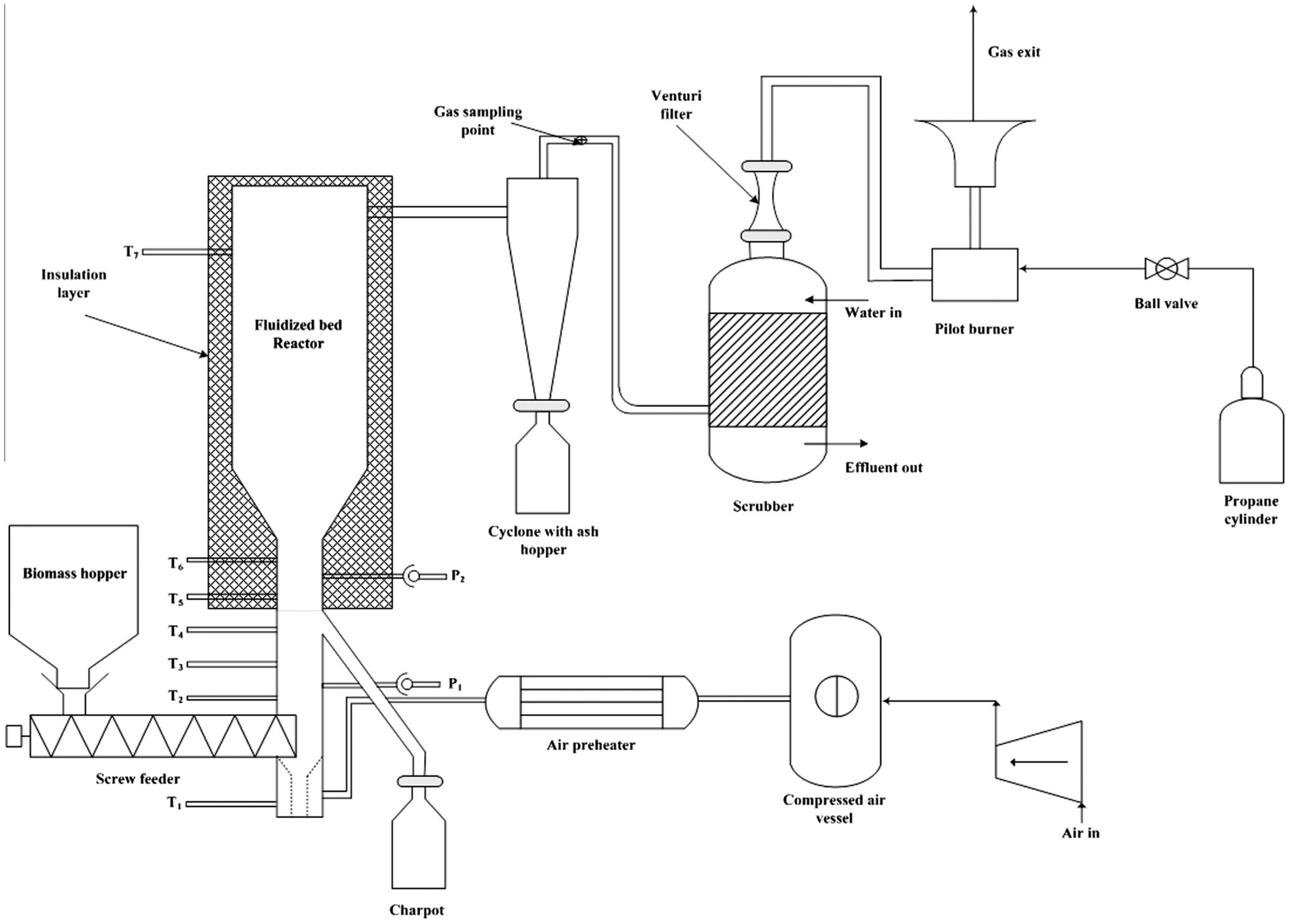

Fig. 1. Schematic diagram of the process flow.

entered into the reactor through the nozzles located at the bottom of the reactor and is regulated by a thermal mass flow controller operating within the range between 0.5 and 100 N m^3/h (Bronkhorst HIGH-TECH, the Netherlands).

2.3.3. Reactor and the measurement sensors

The body of the reactor is made of AISI 310 refractory stainless steel with a diameter and total height of 0.36 m and 3.5 m respectively. The total height is split into two sections, i.e., bed and freeboard with the latter slightly bigger in circumferential area (0.23 m), located above the main body of the gasifier. Insulation layers composed of 0.3 m thick insulating blankets (Unifrax Insulfrax S, Spain) cover the entire reactor from top to the bottom, minimizing heat transfer to the surroundings. Seven thermocouples (T_1–T_7) (bottom-up) as shown in Fig. 1 monitor temperature at various heights of the reactor. Temperature probe T_1 measures temperature at the inlet of the reactor while equidistant thermocouples T_2 through T_6 register temperature variations occurring in and around the bed. Probe T_7 is the uppermost sensor located at the freeboard of the reactor, determining the temperature of the gas exit. Besides the temperature sensors, pressure sensors P_1 and P_2 (Fig. 1) are positioned at the side of the reactor to monitor the fluidization condition of the bed.

2.3.4. Gas cleaning and conditioning

Immediately after the production, gas was cleaned and conditioned by means of a series of devices composed of cyclone, ash hopper and scrubber. First of all, gas leaving from the reactor circulated through a cyclone stripping entrained particles and then through a scrubber removing condensable tars. Char, ash and inactive bed materials were collected in the bins (ash hopper and char pot) located at the bottom of the cyclone and side of the reactor respectively. After each operation the bins were emptied to analyze residue quality and further to account mass balance.

2.3.5. Gas sampling

Part of the gas coming out from the main gas exit to flare (located outside the gasification unit to avoid hazard), was sampled in a sampling train consisting of two tar condensers, a particle filter, a flow meter and a gas analysis system. The entry of the sampling train was continuously heated by an electrical resistance at 450 ± 5 °C to avoid undesired condensation of condensable products in the producer gas before the condensers. As passing through the sampling line, producer gas was first cooled in the two ice condensers (~0.75 L each) and being washed out of the majority of the tars. Cooled gas was then cleaned by a cotton filter before being analyzed for permanent gases by the gas analyzer. The quantity of the gas used for sampling was measured by a gas flow meter, situated in between cotton filter and the analyzer while the quantity of the tar deposited on the condensers was manually recovered at the end of the each gasification test. An estimation of the amount of tar produced was done based on the manual volumetric measurement of the collected liquids in the sampling line while its composition was evaluated by a GC–MS (Gas chromatography-mass spectrometry) (Agilent 7890 A, USA).

2.3.6. Gas analysis equipment

Located furthest to the sampling train, a micro-gas chromatograph (Agilent 3000A μGC, Model G2801A, USA) equipped with two analysis modules (Plot U and Molsieve 5A) and thermal conductivity detectors were used to analyze the permanent gases of the sample taken from the producer gas line. Measurement was conducted real-time (once in every two min) based on the calibration of CO_2, C_2H_4, C_2H_6, C_2H_2 and H_2S for Plot U module, and H_2, N_2, CH_4, CO and O_2 for MolSieve 5A module respectively. The gas composition data continuously produced by the μGC was stored in a computerized data acquisition system for further interpretation.

2.4. Experimental protocols

During start up, the sand constituting the initial reactor bed was heated by the air delivered from the preheater in order to heat up the reactor until the temperatures of around 450–500 °C. The heating up process using the electric heater generally takes around 3 h because of the size of the reactor and the air flow rate necessary to maintain a bubbling fluidized bed regime inside the reactor.

After about 3 h of preheating, bed temperature rose to around 500 °C, at which a small amount of biomass was combusted and rapidly increased the bed temperature to a desired level of ca. 750–800 °C, high enough to initially sustain autothermal conditions during the gasification step. The heat released in the autothermal conditions, with the exception of energy losses, was utilized in the endothermic reactions allowing pyrolysis and gasification reactions to endure.

The initial gasification temperature in this set of experiments was targeted at 800 ± 10 °C, achieved after some 20 min of combustion. Changeover from combustion to gasification conditions and, subsequently, the modification of the ER were obtained by increasing the air flow but keeping the constant biomass feeding rate. For this set of experiments the solids feeding rate was kept stable at 4.7 kg/h whereas air flow rate was varied between 4.16 and 4.99 N m^3/h such that the corresponding ER could be fixed at 0.25 and 0.30 respectively. The ER was calculated by obeying the relationship as follows:

$$ER = \frac{Q_{air}}{Q_{alfalfa} \times 3.54} \qquad (1)$$

The stoichiometric amount of air required for complete combustion of alfalfa pellets was found to be 3.54 N $m^3/kg_{feedstock}$ based on the elemental composition of the pellets and hence given at the denominator of the Eq. (1). The terms Q_{air} and $Q_{alfalfa}$ in Eq. (1) additionally represent the air and feed flow rates in N m^3/h and kg/h respectively.

As gasification conditions were reached and the gasification step was initiated, steady state condition could be achieved in about 20 min of time-on-stream, beyond which further data collection was continued to evaluate the evolution profiles of temperature, gas composition, lower heating value, gas yield and cold gas efficiency as an effect of varied ER. The calculation of the producer gas heating value (in MJ/N m^3), gas yield and cold gas efficiency (CGE) were performed by employing the Eqs. (2)–(4) [31] while the development of temperature, pressure and air flow rate were registered in a data logger, later transferred to a computer for further interpretation.

$$LHV_{producer\ gas} = ((25.7 \times H_2) + (30.0 \times CO) + (85.4 \times CH_4) + (151.3 \times (C_2H_2 + C_2H_4 + C_2H_6))) \times \left(\frac{4.2}{1000}\right) \qquad (2)$$

$$V_{producer\ gas} = \frac{Q_{air} \times 79}{N_2 \times m_{feedstock}} \qquad (3)$$

$$CGE = \frac{LHV_{producer\ gas} \times V_{producer\ gas}}{LHV_{feedstock}} \times 100\% \qquad (4)$$

where $LHV_{producer\ gas}$ is the dry base lower heating value of producer gas in MJ/N m^3; $V_{producer\ gas}$ is the dry gas yield in N m^3/kg_feedstock; Q_{air} is the air supply in N m^3/h; $m_{feedstock}$ is the biomass input in kg/h, $LHV_{feedstock}$ is the dry base calorific value of the pellets in MJ/kg and CGE is the cold gas efficiency in percent.

During the test, the gasifier ran through a transition stint of some 20 min after which temperature stabilization was achieved and continued for about 3 h, followed by the plant shut-down. The steady state was mainly divided into two periods based on the imposed ER ratios, the effect of which was investigated on various operational parameters, i.e., gas composition, LHV, efficiency, gas yield, char yield and tar yield, which are described in the following sub-sections.

3. Results and discussions

3.1. Biomass characterization

Table 2 presents the results obtained from the feedstock characterization.

With regards to moisture, the level found in alfalfa pellets was at ~8.7% (m/m) which compared to a previous work [32] is lower in range. Some amount of moisture helps thermal conversion [33] while too much brings negative consequences, such as the reduction in fuel energy content and process temperature. The value revealed from the present study, as lying below 10%, is expected to avoid the issues related to high moisture content and thus making the raw-material suitable for gasification [34].

Volatiles contents were in the range of 74% (dry fuel basis) which albeit a little lower than that from the study by Sharma [18] in harmony with another work carried out by Boateng and the co-authors [16]. As of ash content, alfalfa pellets displayed an average level of ~15% (dry basis) which is higher than the past study conducted by Boateng et al. [16]. However, since the gasification temperature for the present study did not exceed the melting point of ash, the plant operation was not influenced by its high quantity.

Average lower calorific value after analysis amounted as ~17 MJ/kg (dry base) which can be considered lower than the typical for most of the herbaceous biomass including alfalfa as according to the study by Domalski et al. [35]. The LHV value obtained has been compared to the theoretical LHV that could be calculated according to the empirical correlation proposed by Gaur

Table 2
Physical and chemical properties of alfalfa pellets.

Proximate and ultimate analyses of alfalfa pellets (*n* = 3)	
Proximate analysis (%)	
Moisture	8.73 ± 0.64
Volatile matter	74.4 ± 1.29
Ash	15.5 ± 0.44
Ultimate analysis (dry base, %)	
Carbon	41.60 ± 0.44
Hydrogen	4.90 ± 0.07
Oxygen[a]	33.94 ± 0.48
Nitrogen	2.39 ± 0.15
Sulfur	0.25 ± 0.02
Lower heating value (dry basis, MJ/kg)	
Analytical	16.69 ± 0.98
Theoretical[b]	17.46 ± 0.10

[a] Calculated by difference.

[b] Gaur and Reed [36].

and Reed [36]. The value found from the measurements in the bomb calorimeter is in good concordance to the value obtained using the abovementioned empirical correlation (~17.4 MJ/kg). The ultimate analysis revealed the mean percentages of C, H, O, N and S in the pellets as 41.6, 4.9, 33.9, 2.4 and 0.25% respectively (Table 2). Except the percentage composition of carbon and oxygen, this finding showed a good agreement with the literature [32]. Moreover, the low sulfur, high hydrogen and reasonably acceptable oxygen level make this biomass attractive in the context of gasification.

As per structural composition of alfalfa, results obtained from the literatures vary with the maturity and the different forms of the crops [16,30]. In general, the cellulose content constituted the major composition followed by the lignin and hemicellulose (Table 1). The level of lignin in comparison with other similar feedstocks was found lower in alfalfa [37] which is probably because of high level of nitrogen and low level of carbon containing in its chemical composition. Besides low lignin, the simultaneous variation in cellulose and lignin proportion of different maturities of alfalfa was reported to affect the quality of the oil produced from the pyrolysis of alfalfa in a study conducted by Boateng et al. [16]. Due to the uniformity of the feedstock, corresponding effect of such nevertheless was not observed in the present gasification work.

3.2. Pilot scale fluidized bed gasification

3.2.1. Effect of ER on the quality of producer gas

The effect of ER on the quality of the producer gas was investigated for 0.25 and 0.30. The producer gas was composed of series of gas species CO, CO_2, H_2, CH_4, C_2H_4, C_2H_6 and N_2 the evolution of which over time is depicted by Fig. 2.

As shown, the increase in ER from 0.25 to 0.30 had little effect on the product gas composition where most of the combustible and incombustible components kept stable or reduced. The concentration of CO_2, for example, slightly declined and reached to an average of 19.8 ± 0.2 vol.% at ER = 0.30 compared to the average of 20.2 ± 0.2 vol.% at ER = 0.25 (Figs. 2a and 3h).

This was in contrast with that of the CO, which increased from 8.4 ± 0.01 to 9.1 ± 0.05 vol.%, mainly at the expense of CO_2 and CH_4 (Table 3).

The inverse relationship between CO and CO_2, as observed, is a typical phenomenon of the Boudouard reaction ($C + CO_2 \overset{+heat}{\Longleftrightarrow} 2CO$), evidenced by the many past studies such as the one by Aznar et al. [25]. The extent of such reaction, nonetheless, is not critical in the present findings as the variation of those gas components was rather insignificant for varied ER.

Investigating the concentration of other gas species between the two successive ER, the following results were revealed: H_2 decreased from 13.3 ± 0.3 to 12.8 ± 0.1 vol.%, CH_4 decreased from 2.73 ± 0.04 to 2.66 ± 0.02 vol.%, C_2H_4 decreased from 0.88 ± 0.1 to 0.87 ± 0.03 vol.% and C_2H_6 decreased from 0.26 ± 0.03 to 0.25 ± 0.02 vol.% respectively (Table 3, Figs. 2 and 3h).

As of gas LHV, a positive effect of increasing the ER was observed, displaying an average value of 4.21 ± 0.02 MJ/N m^3 (dry base) for the higher ER compared to an average of 4.19 ± 0.08 MJ/N m^3 (dry base) for the ER = 0.25 (Figs. 2 and 3g). The LHV is a direct function of the combustible quantity which in the present case rose (from 25.3% to 26.0%) as ER rose, and thus accordingly the LHV. As a rule of thumb, the gas LHV at minimum 4.2 MJ/N m^3 (dry base) suits the operation of an internal combustion (IC) engine [38], yielding simultaneous heat and electricity. Based on gas LHV, the present experiments at ER = 0.30 favors that application and hence promising in terms of fluidized bed gasification.

In terms of gas yield, which is an important parameter to determine the productivity of gasification, a similar pattern to that of LHV was observed where the increase in ER from 0.25 to 0.30 caused the gas yield to rise from 1.36 ± 0.00 to 1.52 ± 0.02 N m^3/kg (Fig. 3g). This trend is in agreement with several past studies that dealt with similar gasification investigations [25,39]. The prime reason of this gas yield behavior is possibly related to the high rate of devolatilization [24] which was successively greater as a result of the higher ER. Several endothermic reactions such as char gasification, steam reforming and tar cracking are also significantly favored when air supply is increased and thus contribute to augment gas production [25].

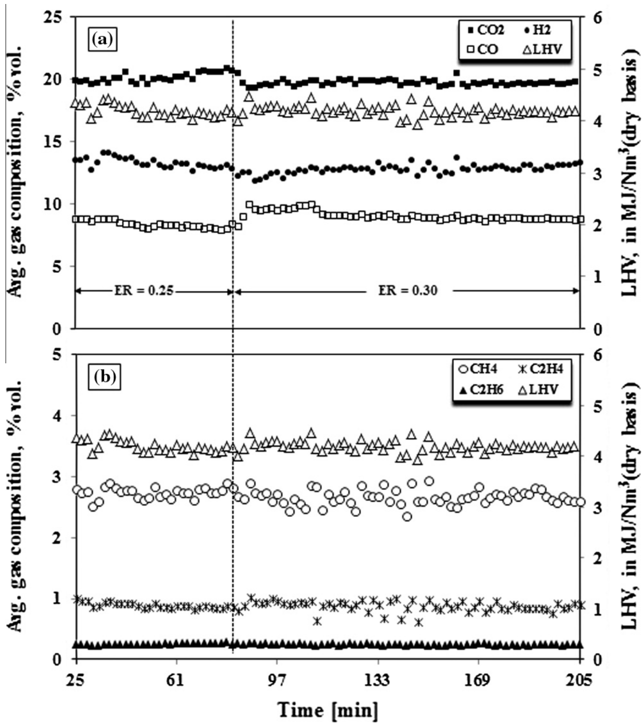

Fig. 2. Continuous evolution of gas composition and its lower heating value as a function of ER.

Unlike preceding parameters, the effect of each ER change on char and tar yields were impossible to examine as the ER varied on-line and the measurement (of tar and char) conducted off-line. However, the total char and tar yield for the whole ER range at the end of each experiment was analyzed and found as 281.7 ± 28.0 g/kg and 1.12 ± 0.04 g/N m^3 respectively (Fig. 3i, Table 3), closely coinciding with the previous studies dealing with the downdraft gasification of alfalfa and fluidized bed co-gasification of coal, biomass and plastic waste respectively [18,25].

As a direct function of LHV and producer gas quantity, the cold gas efficiency (CGE) exhibited a higher value (38.5 ± 5%) for the higher ER, with a difference as much as 10% (Table 3 and Fig. 3g) for that of lower ER. Definitely, efficiency in the range of 60% or less suggests low productivity which perhaps was associated with the lower yield of the combustible gases, i.e.; the yield of CO, H_2, CH_4 etc., and the development of lower gasification temperature, that peaked slightly below 800 °C at the present investigations. Similar phenomenon with regards to the low CGE was also observed by Gómez-Barea et al. [24].

3.2.2. Effect of ER on operational temperatures

Fig. 3 illustrates the temperature profiles of various sensors (T_1–T_7) and their corresponding effect on ER.

As observed (Fig. 3f), T_7 exhibited the lowest of all the temperatures due to its location close to the gas exit, in vicinity to the top of the reactor. This sensor was assigned to record the temperature

Table 3
Summary of the operational parameters obtained from the gasification of alfalfa pellets.

Operational parameters	Run 1		Run 2	
	ER = 0.25	ER = 0.30	ER = 0.25	ER = 0.30
Air input (N m^3/h)	4.16	4.99	4.16	4.99
Biomass feed (kg/h)	4.7		4.7	
CO (vol.%)	8.43 ± 0.31	9.08 ± 0.03	8.42 ± 0.35	9.15 ± 0.48
H_2 (vol.%)	13.02 ± 0.45	12.91 ± 0.31	13.50 ± 0.60	12.73 ± 0.53
CH_4 (vol.%)	2.77 ± 0.11	2.67 ± 0.14	2.70 ± 0.15	2.65 ± 0.27
C_2H_4 (vol.%)	0.81 ± 0.05	0.89 ± 0.07	0.95 ± 0.07	0.85 ± 0.16
C_2H_6 (vol.%)	0.25 ± 0.02	0.23 ± 0.02	0.25 ± 0.01	0.26 ± 0.01
CO_2 (vol.%)	20.31 ± 0.41	19.6 ± 0.28	20.04 ± 0.48	19.9 ± 0.29
N_2 (vol.%)	51.5 ± 0.74	50.6 ± 1.0	54.14 ± 0.96	54.45 ± 0.84
Lower heating value (MJ/N m^3)	4.13 ± 0.13	4.21 ± 0.15	4.25 ± 0.17	4.19 ± 0.16
Specific gas yield (N m^3/kg_fuel)	1.36 ± 0.02	1.66 ± 0.03	1.35 ± 0.19	1.38 ± 0.03
Cold gas efficiency (%)	33.8 ± 1.05	42.14 ± 1.26	34.76 ± 1.4	34.85 ± 1.56
Char yield (g/kg)	301.52		261.92	
Tar yield (g/N m^3)	1.15		1.09	

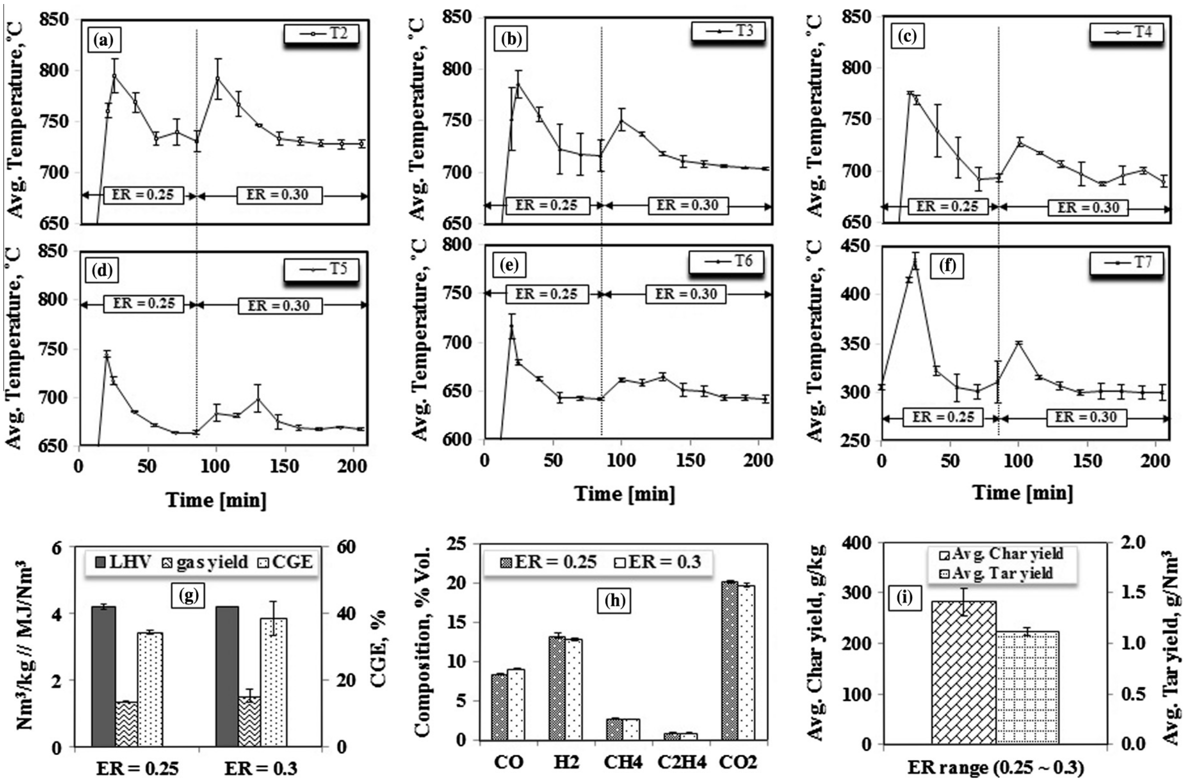

Fig. 3. Effect of ER on various operational variables.

of the freeboard. Temperatures registered by T_3 (Fig. 3b) may be associated with gasification due to its operating range situating nearest to the temperature of combustion, which was likely to be detected by sensor T_2 (Fig. 3a). The combustion temperature may also be defined as the temperature of bed. Among all the probes, thermocouple T_4 (Fig. 3d) showed the temperature variation in proximity to the overflow – collecting the unburned char and ash, and hence may be assigned to reduction. Being the closest neighbors to the freeboard, pyrolysis may be recognized by thermocouples T_5 and T_6 (Fig. 3d and e) as showing a lower temperature than those of combustion, gasification and reduction.

In general, temperatures developed in all the sensors increased with ER and maintained distinctive differences between themselves (Fig. 3a–f). This is somewhat logical as the energy available to the bed improves with the quantity of oxygen available more heat is supplied to the reactor as a result of enhanced combustion. In addition to the rise in temperature, increased oxygen also influenced the several operational variables, the relations of which with the bed temperature are presented in Fig. 4.

As for gas composition (Fig. 4a–e), CO content increased with bed temperature and H_2 decreased. This was in contrast with the study by Hanping et al. [39] according to which both CO and H_2 increased as the bed temperature increased. However, the increasing extent of these gases was reported to be tender for the bed temperature lower than 800 °C. The development of low bed temperature in the present study agrees with the past work and hence indicates why the effect of temperature was less pronounced in the evolution profile of CO and H_2. The tendency of variation among the other combustible gases (such as, CH_4, C_2H_4 and C_2H_6) was not so significant, although slight increasing and decreasing trends were noticed. Theoretically, the severity of several reforming and cracking reactions increase as a result of a higher bed temperature

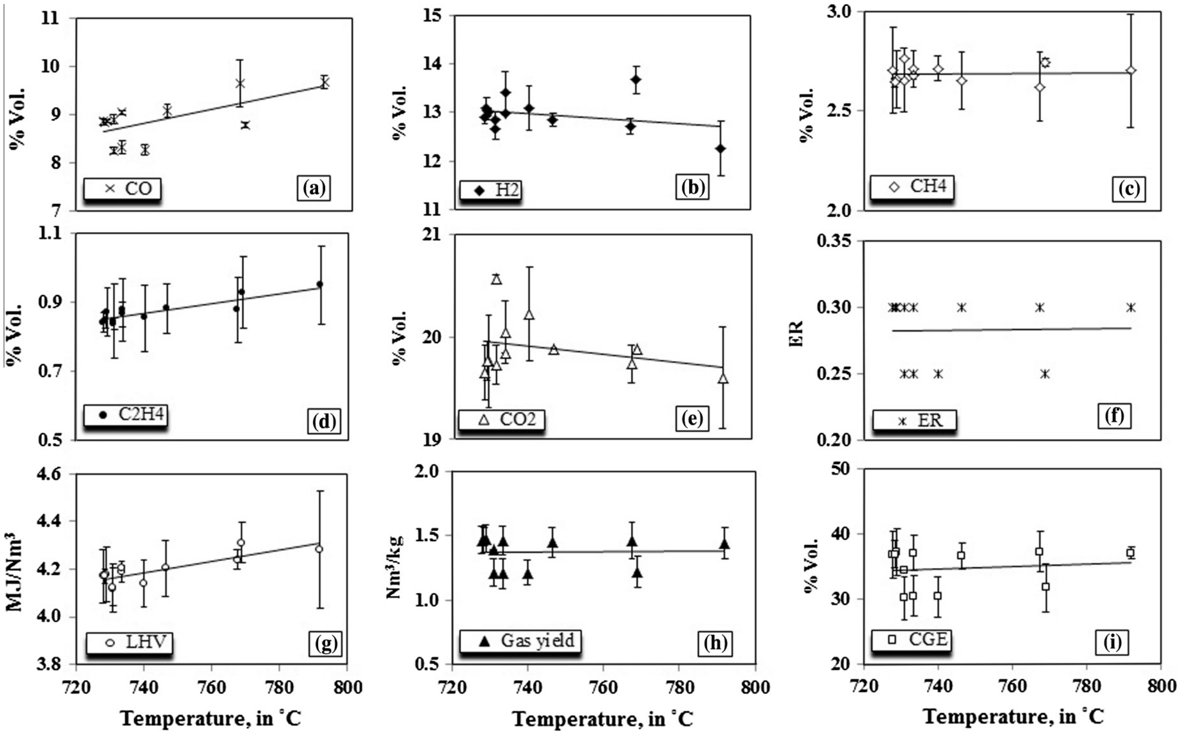

Fig. 4. Influence of bed temperature on the production trend of several operational variables.

Table 4
Identification of the tar components deposited in the condensers.

Run 1				Run 2			
Condenser 1		Condenser 2		Condenser 1		Condenser 2	
Peaks	Compounds	Peaks	Compounds	Peaks	Compounds	Peaks	Compounds
11.548	3-methyl-Pyridine	11.791	3-methyl-Pyridine	11.782	3-methyl-Pyridine	11.801	3-methyl-Pyridine
17.310	Phenol	17.333	Phenol	17.399	Phenol	17.453	Phenol
20.902	2-methyl-Phenol	19.244	Benzonitrile	19.244	Benzonitrile	20.905	2-methyl-Phenol
21.188	2-Aminopyridine	21.825	3-methyl-Phenol	20.886	2-methyl-Phenol	21.335	2-Aminopyridine
21.826	3-methyl-Phenol	24.368	4-ethyle Benzenamine	21.245	2-Aminopyridine	21.897	3-methyl-Phenol
24.379	4-ethyle-Benzenamine	30.076	N-2-propenyl-Benzenamine	21.866	3-methyl-Phenol	23.569	4-ethyle Benzenamine
						23.949	2.5-dimethyl-2-Hexane
						24.423	4-ethenyl Benzenamine
				31.958	Isoquinoline	30.89	N-dimethyl-N Phenylenediamine
36.013	Indole	32.876	Quinoline	36.038	Indole	32.927	Quinoline

and thus participate in the production of higher amounts of H_2 and CO. In the present case, the involvement of reforming and cracking reactions are only implied by the trend of CO, but rather unnoticed by H_2 as the latter slightly dropped throughout (Fig. 4b).

Despite the insignificant effect on individual gas species, the total combustible quantity slightly rose (from 25.3 to 26 vol.%) with temperature and reflected to the gas LHV as shown in Fig. 4g. As the bed temperature rose, the total CO as well as the CH_4 content increased, in spite of reduced H_2, and thus contributed to a net rise in gas calorific value. Likewise LHV, the average gas yield and the CGE also peaked with a rise in the bed temperature (Fig. 4h and i). The reason of the improved gas yield may be explained by the rate of solid–gas reactions, which increased as a result of the heightened bed temperature.

3.3. Tar characterization

Although a direct relationship between each ER change and tar yield could not be established, the total tar yield after gasification was measured both for volume and composition. The volumetric tar yield data has already been presented in the preceding section. This section only discusses compositional tar.

As already mentioned, GC–MS was employed for evaluating tar composition which was grouped as according to the point of sampling: such as upstream (condenser close to the sample entrance – condenser 1) and downstream (condenser further to the sample entrance – condenser 2). The tar abundances and their corresponding peaks with identifications for two sampling points are demonstrated by Table 4.

As observed, the abundance of tar compounds varied with the sampling locations. Peaks were in general found more frequent and higher for condenser 2 as compared to that of condenser 1. Among the twelve identified components, phenol, 3-methyl-phenol and 3-methyl pyridine were common between the two condensers. Tar of these types, especially the phenols, are the organic compounds of 6 carbons, yielded due to pyrolytic degradation of lignin [40]. Another reason of the high availability of phenols in the tar spectra is the low gasification temperature, the increase of which contributes to convert those into gaseous products. Apart from the phenols, the other detected compounds were predominantly the nitrogen containing tars specified as 2-amino-piridyne and indole found in condenser 1, and benzonitrile, N-2-propenyl-benzenamine, 2.5 dimethyl – 2-Hexane, N-dimethyl-N-phenylenediamine and quinolone found in condenser 2 respectively (Table 4). The presence of nitrogen in the tar sample is perhaps originated from fuel N, the degradation of which in general increases with the increase in operation temperature [40]. High gasification temperature also contributes to the production of PAHs (Poly aromatic hydrocarbons: naphthalene, acenaphthene, anthracene, phenanthrene etc.) which logically was not detected in the present analysis. Among the aromatic compounds identified, quinoline was by far the heaviest (~129 g/mol) molecule potentially caused the stringent odor to the nearby environment while indole, a medium sized heterocyclic aromatic compound, appeared to be a major source of fragrances as the analysis revealed.

4. Conclusions

This work examined the performance of pilot scale bubbling fluidized bed gasification of alfalfa pellets at varied ER. Most of the important parameters including bed temperature demonstrated an increasing trend as the quantity of input air improved. The average gas LHV for instance reached to a level > 4.2 MJ/N m^3 which is interesting in-terms of energy conversion via gas engine. Additionally, the cold gas efficiency and the gas yield peaked at ~39% and ~1.6 N m^3/kg (dry basis) respectively as an impact of increased ER. Good gasification properties including with the suitability of producing distributed energy make alfalfa a promising biomass to introduce for FB processing, as the preliminary study thus far revealed.

Acknowledgements

This study was conducted at Thermochemical Process Group (GPT) from the Universidad Zaragoza (UNIZAR), Spain, financed jointly by the University of Agder (UiA), Norway and BRISK (Biofuel Research Infrastructure for Sharing Knowledge), EU, under the framework of UZR2-22-04-13 BRISK TNA. The authors wish to thank both of these funding bodies. The lab facility and the assistance from a number of scientific personnel offered by UNIZAR are regarded core of this work and therefore are highly noted.

References

[1] Kirkels AF, Verbong GPJ. Biomass gasification: Still promising? A 30-year global overview. Renew Sustain Energy Rev 2011;15:471–81.
[2] Saxena R, Adhikari D, Goyal H. Biomass-based energy fuel through biochemical routes: a review. Renew Sustain Energy Rev 2009;13:167–78.
[3] Caliandro P, Tock L, Ensinas AV, Marechal F. Thermo-economic optimization of a solid oxide fuel cell–gas turbine system fuelled with gasified lignocellulosic biomass. Energy Convers Manage 2014;85:764–73.
[4] Barnes D, Froese RE, Mannes RG, Warner B. Combined sustainable biomass feedstock combustion, CO_2/EOR, and saline reservoir geological carbon sequestration in Northern Lower Michigan, USA: towards negative CO_2 emissions. Energy Procedia 2011;4:2955–62.
[5] Möllersten K, Yan J, Moreira JR. Potential market niches for biomass energy with CO_2 capture and storage—opportunities for energy supply with negative CO_2 emissions. Biomass Bioenergy 2003;25:273–85.
[6] Alauddin ZABZ, Lahijani P, Mohammadi M, Mohamed AR. Gasification of lignocellulosic biomass in fluidized beds for renewable energy development: a review. Renew Sustain Energy Rev 2010;14:2852–62.
[7] Zhang K, Chang J, Guan Y, Chen H, Yang Y, Jiang J. Lignocellulosic biomass gasification technology in China. Renewable Energy 2013;49:175–84.
[8] Barman NS, Ghosh S, De S. Gasification of biomass in a fixed bed downdraft gasifier–A realistic model including tar. Bioresour Technol 2012;107:505–11.
[9] Sarker S, Nielsen H. Preliminary fixed-bed downdraft gasification of birch woodchips. Int J Environ Sci Technol 2014. <http://dx.doi.org/10.1007/s13762-014-0618-8>.
[10] Bimbela F, Oliva M, Ruiz J, García L, Arauzo J. Steam reforming of bio-oil aqueous fractions for syngas production and energy. Environ Eng Sci 2011;28:757–63.
[11] Wang L, Weller CL, Jones DD, Hanna MA. Contemporary issues in thermal gasification of biomass and its application to electricity and fuel production. Biomass Bioenergy 2008;32:573–81.
[12] Alipour Moghadam R, Yusup S, Azlina W, Nehzati S, Tavasoli A. Investigation on syngas production via biomass conversion through the integration of pyrolysis and air–steam gasification processes. Energy Convers Manage 2014;87:670–5.
[13] Campoy M, Gómez-Barea A, Ollero P, Nilsson S. Gasification of wastes in a pilot fluidized bed gasifier. Fuel Process Technol 2014;121:63–9.
[14] Gil J, Corella J, Aznar MaP, Caballero MA. Biomass gasification in atmospheric and bubbling fluidized bed: effect of the type of gasifying agent on the product distribution. Biomass Bioenergy 1999;17:389–403.
[15] Boateng A, Jung H, Adler P. Pyrolysis of energy crops including alfalfa stems, reed canarygrass, and eastern gamagrass. Fuel 2006;85:2450–7.
[16] Boateng AA, Mullen CA, Goldberg N, Hicks KB, Jung H-JG, Lamb JF. Production of bio-oil from alfalfa stems by fluidized-bed fast pyrolysis†. Ind Eng Chem Res 2008;47:4115–22.
[17] Butterman HC, Castaldi MJ. Influence of CO_2 injection on biomass gasification. Ind Eng Chem Res 2007;46:8875–86.
[18] Sharma A. Assessing the suitability of various feedstocks for biomass gasification. Louisiana State University; 2011.
[19] González-García S, Moreira MT, Feijoo G. Environmental performance of lignocellulosic bioethanol production from Alfalfa stems. Biofuels Bioprod Biorefin 2010;4:118–31.
[20] Buragohain B, Mahanta P, Moholkar VS. Biomass gasification for decentralized power generation: the Indian perspective. Renew Sustain Energy Rev 2010;14:73–92.
[21] Mani S, Sokhansanj S, Bi X, Turhollow A. Economics of producing fuel pellets from biomass. Appl Eng Agri 2006;22:421.
[22] Arjharn W, Hinsui T, Liplap P, Raghavan G. Evaluation of electricity production from different biomass feedstocks using a pilot-scale downdraft gasifier. J Biobased Mater Bioenergy 2012;6:309–18.
[23] Elder T, Groom LH. Pilot-scale gasification of woody biomass. Biomass Bioenergy 2011;35:3522–8.
[24] Gómez-Barea A, Arjona R, Ollero P. Pilot-plant gasification of olive stone: a technical assessment. Energy Fuels 2005;19:598–605.
[25] Aznar MP, Caballero MA, Sancho JA, Francés E. Plastic waste elimination by co-gasification with coal and biomass in fluidized bed with air in pilot plant. Fuel Process Technol 2006;87:409–20.
[26] Kim YD, Yang CW, Kim BJ, Kim KS, Lee JW, Moon JH, et al. Air-blown gasification of woody biomass in a bubbling fluidized bed gasifier. Appl Energy 2013;112:414–20.
[27] Narobe M, Golob J, Klinar D, Francetič V, Likozar B. Co-gasification of biomass and plastics: pyrolysis kinetics studies, experiments on 100 kW dual fluidized bed pilot plant and development of thermodynamic equilibrium model and balances. Bioresour Technol 2014;162:21–9.
[28] Yu MM, Masnadi MS, Grace JR, Bi X, Lim CJ, Li Y. Co-gasification of biosolids with biomass: thermogravimetric analysis and pilot scale study in a bubbling fluidized bed reactor. Bioresour Technol 2014.
[29] Fanlo R, Chocarro C, Lloveras J, Ferran X, Serra J, Salvia J, et al. Alfalfa production and quality in Northeast Spain. Grassland Sci Europe 2006;11:261–3.
[30] Phyllis2, database for biomass and waste, ECN, The Netherlands. <https://www.ecn.nl/phyllis2>. Last accessed: 21/10/2014.
[31] Sarkar M, Kumar A, Tumuluru JS, Patil KN, Bellmer DD. Gasification performance of switchgrass pretreated with torrefaction and densification. Appl Energy 2014;127:194–201.
[32] Jenkins B, Baxter L, Miles Jr T, Miles T. Combustion properties of biomass. Fuel Process Technol 1998;54:17–46.
[33] Acharjee TC, Coronella CJ, Vasquez VR. Effect of thermal pretreatment on equilibrium moisture content of lignocellulosic biomass. Bioresour Technol 2011;102:4849–54.
[34] García R, Pizarro C, Lavín AG, Bueno JL. Characterization of Spanish biomass wastes for energy use. Bioresour Technol 2012;103:249–58.
[35] Domalski ES, Jobe Jr TL, Milne TA. Thermodynamic data for biomass conversion and waste incineration. National Bureau of Standards, Washington, DC (US); Solar Energy Research Inst., Golden, CO (US); 1986.
[36] Gaur S, Reed TB. An atlas of thermal data for biomass and other fuels. Golden, (CO, (United States): National Renewable Energy Lab.; 1995.
[37] Demirbas A. Combustion characteristics of different biomass fuels. Prog Energy Combust Sci 2004;30:219–30.
[38] P. Quakk, H. Knoef, H. Stassen. Energy from biomass: a review of combustion and gasification technology. World Bank Technical Paper; 1999.
[39] Hanping C, Bin L, Haiping Y, Guolai Y, Shihong Z. Experimental investigation of biomass gasification in a fluidized bed reactor. Energy Fuels 2008;22:3493–8.
[40] Li L, Huang S, Wu S, Wu Y, Gao J, Gu J, et al. Fuel properties and chemical compositions of the tar produced from a 5 MW industrial biomass gasification power generation plant. J Energy Inst 2014.